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# A global survey of gas hydrate development and reserves: Specifically in the marine field

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ABSTRACT

Gas hydrates, also known as methane hydrates, are formed due to the high hydraulic pressures present under the cold seabed over long periods of time. Gas hydrates are mainly composed of methane produced in the seabed by bacteria in the use of the remains of animals and plants as food. Often appearing as translucent or opaque ice, gas hydrates can be separated into water and methane gas, which can be burned at normal temperatures and pressures, giving this substance the nickname "combustible ice." As global oil reserves continue to be depleted, scientists are regarding methane hydrates as a new energy source that is very likely to replace oil in the 21st century. According to reports by the United States Geological Survey, the potential natural gas energy that can be recovered from global methane hydrate formations is two times the amount of fossil fuel energy available to the world. Therefore, many countries that are deeply engaged in the development of gas hydrates, such as the United States, Japan, Canada, China, India, and Taiwan, hope that this new energy source can become a substitute for more conventional petroleum sources. Japan—the first country to develop methane hydrates—will be ready for commercial mass production in the eastern Japanese Nankai Trough prior to 2018, according to Japan's Methane Hydrate R&D Program-MH 21. However, the exploitation of methane hydrates in terrestrial permafrost requires less technical risk and costs. Joint explorations in areas of Alaska by the United States, Japan, and Canada will enter the preparation phase for commercial output as early as 2015. In Taiwan, cooperation with Germany and the United States has led to methane hydrate exploration and the initiation of drilling sampling in the South China Sea that is expected to be completed in 2016, with commercial production ready as soon as 2026.



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## 1. Introduction

As formed at low-temperature and high-pressure environment, "Gas Hydrate (natural gas hydrate)" is an ice-like crystalline compound rich in molecules of gas and water. Gas hydrates are composed of various gas molecules, like, methane, ethane, propane, isobutane, n-butane, nitrogen, carbon dioxide, hydrogen sulfide, etc., since dominated by methane gas, gas hydrates are also known as methane hydrates. Gas hydrate—coherently a solid natural gas in the presence of ice-like appearance in nature—can be burned at ambient temperature and pressure, and so it is also known as "combustible ice."

Natural gas hydrate occurrence can often be found in the permafrost at high latitudes/altitudes or in the sedimentary layers of deep waters on the continental margins [1,2]. Also, there is a small part stored in lakes, such as the continental inland seas of Caspian Sea, Black Sea, and Lake Baikal. Today, natural gas hydrates have been proven with abundant reserves in deep water or mountain permafrost regions, such as South China Sea, the Gulf of Mexico, Indian Ocean, Arctic Alaska, Siberia, and multiple regions in Qilian, mainland China [3–6].

Most of the gas hydrate occurs in the shallow crust: below the ground surface within 2000 m or under the seabed within 1100 m, in which the gas hydrate is easily dissociated, because of the changes of temperature or pressure in the external environment. Caused by the weak formations of gas hydrates composed of high-pressure gas and water, disasters such as seabed collapse, slip, subsidence, methane escaping or gusher are most likely to occur during the oil and gas drilling engineering process. Therefore, methane hydrate is not only a new energy treasure, but also an important factor involving the seabed stability and the natural environment system changes [7–10]. Under the premise of compliance with environment and security, how to achieve the goals of sustainable development of methane hydrate resources will be a major challenge for the research fields of future science and engineering.

## 2. Global gas hydrates development overview

Currently the reserve estimation of global methane hydrate resources is still inconclusive. The total volume of methane contained in situ methane hydrates is about between 200 and 3,000,000 trillion cubic meters at standard temperature and pressure [11]. Herein, the amount of global methane hydrate resources in the most commonly cited estimates is about 20,000 trillion cubic meters. The total organic carbon contents are up to 10 trillion metric tons, about two times the currently known global traditional fossil energy resources (coal, oil, natural gas) [1]. In today's growing shortage of conventional energy sources, countries from across the world such as USA, Canada, Japan, India, China and South Korea are competing in the gas hydrates resources investigation in their own economic waters. Because of a wide distribution and a large amount of resources, methane hydrate has been regarded as a new potential energy resource in the 21st century [1,12–14]. It is estimated that gas hydrate will begin small-scale commercial development and gradually become the global natural gas main supply sources during 2020 to 2030 [15].

Methane hydrate is not just another type of natural treasure, but also an important factor in relation to global climate change and continental plate/seabed slope stability [16–19]. Therefore, how to balance the environmental protection and energy security to achieve the goals of sustainable development of methane hydrate resources is a major challenge for science and engineering in the future. Since mid-1990, the United States, Japan, India, Canada, Taiwan and China have gradually invested huge funds to carry out natural gas hydrate research and exploitation activities within their waters and territories. Especially, the developed countries have completed gas hydrate drilling and surveys in their selected areas and actually confirmed the methane hydrate reserves. On the other hand, the production and development methods as well as environmental impact assessment are also actively being undertaken. The goal of quasi-commercial development is expected to be met by 2016 [20].

Although methane hydrates is a future energy with great potential and also among the main factors in relation to the global warming phenomenon, the producible scale of global methane hydrate is still very uncertain, especially their geographical distribution and depth distribution. The known hydrate accumulations and global distribution of appropriate conditions for methane hydrate formation are shown in Fig. 1. In 2008, energy and climate experts aggregated in a global workshop of methane hydrates [21]. They confirmed that the global gas hydrates reserve is more than one trillion tons of carbon equivalents, while the global reserve of 1–10 trillion tons of carbon equivalents is moderately credible. In general, the global methane hydrate reserves are equivalent to 2000–20,000 trillion cubic meters of natural gas. For the sake of comparison, the global coal reserve is about 5 trillion tons of carbon equivalent [22]. Thus, it can be roughly sketched out that the global reserves of coal and gas hydrates are approximately at the same level.

Today, the global energy system is heavily dependent on hydrocarbons, especially on oil, but there are more and more inclinations to use natural gas. While eighty percent of global energy supplies are from fossil energy sources, the decarburization of energy supply is a historical evolution. First of all, since ancient times, humanity had used carbon-intensive biofuels, such as wood; then wood was replaced by coal after the industrial revolution, but coal was in turn replaced by petroleum after the invention of automobile, such that the carbon intensity of the main energy use was further reduced. The two main energy conversion processes took a total time of about 50 years [24]. Based on this technological change inertia to predict the future energy-use conversion tends, it is almost impossible to turn the major energy use into non-carbon energy completely before the middle of the 21st century. Even though from the perspective of climate change, adopting the non-carbonized energies is a desirable strategy, because global emissions would climb to peak within the next two decades, and the growth of carbon emissions would decline to zero at the end of this century, if the average global temperature rise is limited to less than about two Celsius [25].

To prevent the dangerous anthropogenic interference with the climate system, there will be a huge gap between the energy demand and the carbon reduction requirements, thus providing a key opportunity for methane hydrate to become a primary energy supply for human society. Essentially, natural gas is a bridge to convert the high-carbon-intensive fossil energy into the zero-emission energy, because methane is a hydrocarbon with the lowest carbon intensity. Even if just a small part of these huge gas hydrates reserves gets developed, it is enough to allow the human energy use to get into the so-called "Methane Times" [26].

More specifically, even if as little as one-thousandth of the entire methane hydrate is under development, it is then enough to satisfy the global energy demand for one year. However, this energy revolution can only be realized through technical innovation and change, such as a higher level of geological knowledge or a forward-looking economic concept. Especially, it might be contributed by specific economic factors, such as high oil price.

First of all, the characteristics of various hydrates sediments are significantly different. As these different characteristics, humanity must face a variety of technical and technological challenges.

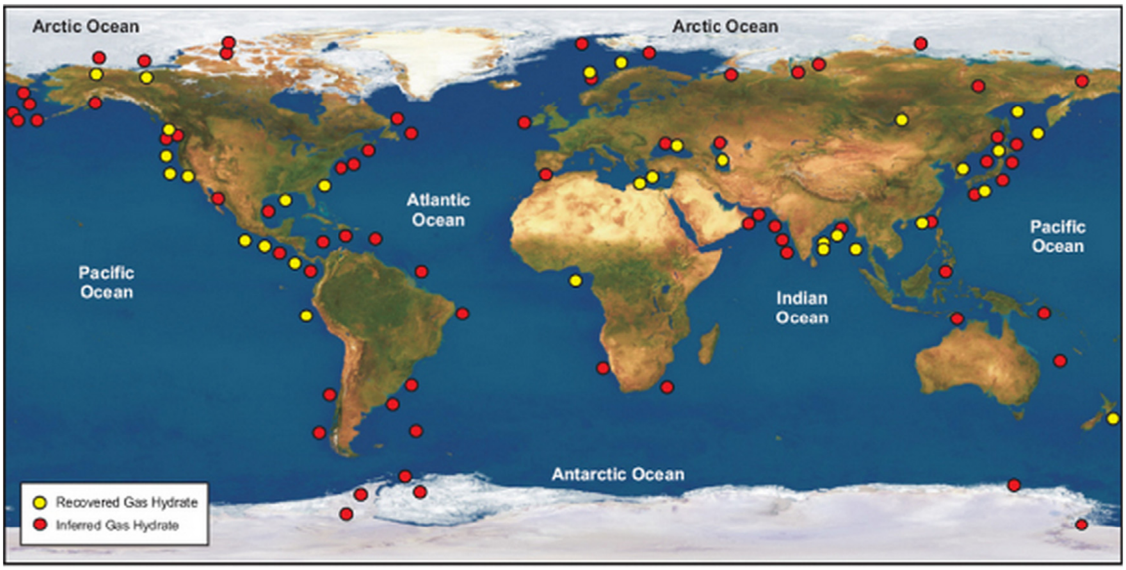


**Fig. 1.** Global known methane hydrate deposits distribution [23,2].

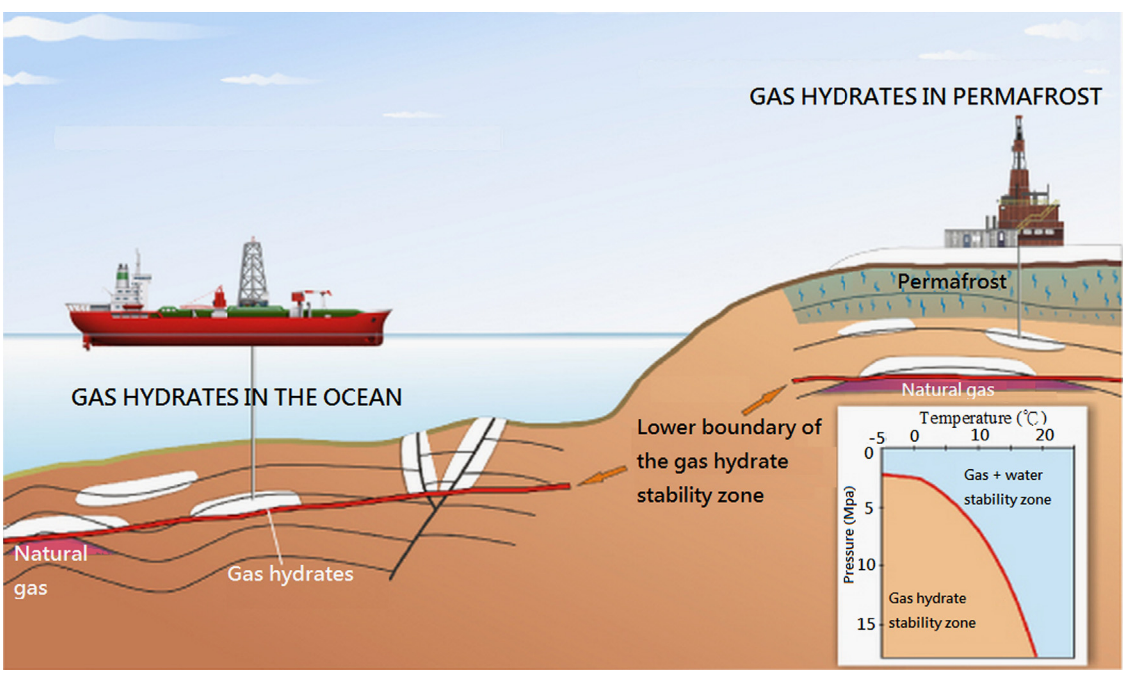


**Fig. 2.** Mining methane hydrates from the land semi-permafrost and the sediments of offshore coast edge (Courtesy of Bundesanstalt für Geowissenschaften und Rohstoffe). The bottom right figure shows the formation of methane hydrate under appropriate conditions of temperature and pressure.

**Table 1**
Exploited combustible ice gas (mines) fields [32].

| Gas mine type | (Mine) field location | Exploitation country |
|---|---|---|
| Land area combustible ice | Mackenzie Delta gas field, Canada | United States, Japan, and Canada |
| | Messoyakha combustible ice ore field, Russia | Former Soviet Union, Russia |
| | Brudhoe Bay-Kuparuk River, North Alaska, United States | United States |
| Marine combustible ice | Nankai Trough, Japan | Japan |

In the terrestrial semi-permafrost layer, gas hydrates can be exploited, as long as there is use of semi-traditional techniques. In fact, in Messoyakha of Western Siberia, some parts of the natural gas extracted from gas fields likely come from hydrates, although a certain amount, and evidence is controversial [27,28]. Making full use of existing infrastructure, such as in West Siberia and Alaska North Slope, will significantly enhance the hydrate mining economy. The current technology expansion, of course, can also be used to exploit marine hydrates, but changes in production technology mode are needed, for example, the uses of automatic and combined exploration/production machines, because methane concentration in the seabed sediments is low [29]. Fig. 2 illustrates the gas hydrate mining processes in Arctic permafrost and on continental offshore margins. The exploration sectors need to break through today's existing technology significantly to be able to successfully develop these resources. The gas hydrates' mining priorities currently concluded by experts are: first, the terrestrial semi-permafrost hydrates; second, the offshore stacked layers in seabed close to land or consumers; and finally, the long-range submarine accumulation layers.

**Table 2**
The average annual cost of each national gas hydrate research and development plans before 2007.

| Governments | Average annual cost |
|---|---|
| Japan | About 50 million USD[a] |
| India | About 35 million USD[a] |
| United States | About 19 million USD[a] |
| China | About 10 million USD[a] |
| Korea | About 3–6 million USD[a] |
| Taiwan | About 1.4 million USD[b] |

[a] Source of data: http://energy.usgs.gov/flash/NaturalGasHydrates.swf.
[b] Source of data: [33].

On the other hand, the development of gas hydrate is also affected by the alternative energy resources policy in each country, especially driven by energy supply security and the worry of shortage. Therefore, the currently vigorously developing countries are those countries with limited domestic resources or with increasing energy demands. For example, Japan, Korea, Taiwan, India, China, and the United States currently have a large research and development program under way [30], as shown in Tables 1 and 2. Therefore, formal commercial production will likely commence before 2020, and expand to other locations and countries in the subsequent decade.

Methane hydrates can be regarded as a midterm alternative energy option, or as a bridge for humanity to enter into the carbon-free energy era. In the meantime, to realize the maximum potential of methane hydrates utilization, under the global demand of $CO_2$ emissions stability, carbon capture and storage technology is still needed. If methane is extracted and combusted at the present site, carbon dioxide hydrate can be deposited simultaneously in the ground or under the seabed. Because current global reserves of methane hydrates and coal are at the same level, extraction technologies with any large storage capabilities will mitigate the anthropogenic climate change significantly [31].

Marine gas hydrates in the seabed will produce tremendous pressure at the instance of releasing, which might damage the undersea environment, and which has been a long-term problem with countries around the world and becomes the bondage to exploit the combustible ice in seabed. Therefore, experts believe that the land combustible ice mining prospect is more optimistic than marine gas hydrates. Moreover, the combustible ice formation in the permafrost zone is shallow and the extraction difficulty is low. It is easier to control the appeared factors, such as disastrous consequences. All these experiences might help in understanding the formation and storage of natural gas hydrates with a great significance in finding these new energy sources.

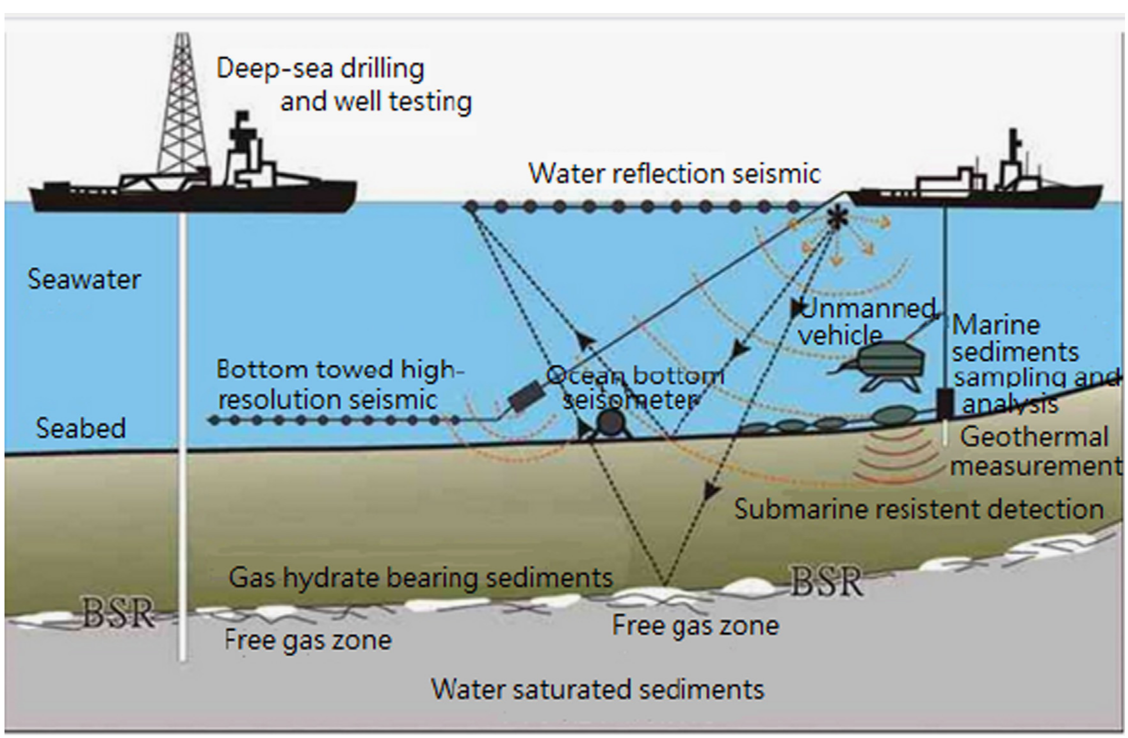


**Fig. 3.** Various methods for the detection of gas hydrates under sea, including the reflection seismic, submarine detection seismograph, submarine detection resistor, ground heat measurement, sampling and analysis of marine sediments, submarine camera or unmanned underwater vehicles observation, deep-sea drilling and well testing and so on [34].

Meanwhile, it also provides a testing ground and technical studies for the exploitation in marine hydrates. From the experiences of other countries, the initial trial mining process of each country was found to mostly focus on the terrestrial gas hydrates fields.

## 3. Gas hydrates detection technology

Refer to Fig. 3. Generally, geophysical methods are the first methods used for the detection of submarine gas hydrates, such as reflection seismic, ocean bottom seismometer, submarine ground resistance, etc., whereby the analysis of underlying characteristics of seabed and the identification of gas hydrate occurrence can be executed. On the other hand, geothermal measurement can estimate the depth of the seabed where gas hydrates can exist stably, thereby carrying out the geochemical analyses for the seabed sediments and samples [34].

Refer to Fig. 4. Currently in the world, the main assessment technique for seabed gas hydrate reserves is the seismic reflection characteristics by Bottom Simulating Reflector (BSR). When the submarine simulating reflection is detected, it is generally believed that there is natural gas hydrates formed in the sedimentary layers, thus making the formation properties tend to homogenize without significant reflection signal (anti-white phenomenon), as shown in Fig. 4, in which the shock propagation speed becomes faster in this layer. However, when there is gas sealed beneath the solid gas hydrate layer, the propagation velocity of seismic waves becomes slower, and then the interface high impedance contrast is formed on the bottom of the methane hydrate stability zone, resulting in a strong reflection phenomenon, namely by the submarine simulating reflector.

Parody seabed reflected signals are similar to the bottom reflection in morphology but opposite in phase, of which the reflection coefficient is shown as a negative value, representing that the overlying layer in the reflecting surface is a high-speed layer (solid gas hydrate), while the lower layer is a low-speed layer (gaseous gas). The depth of Parody seabed reflection is close to the depth of gas hydrate stability zone, which may indicate the maximum depth of gas hydrate formation. Submarine simulating reflector surface is substantially parallel to the seabed, which is mainly affected by the geothermal gradient (i.e., the temperature of deeper seabed is higher than the temperature of the gas hydrate stability zone). As the seabed depth increases, Parody seabed surface reflection depth increases as well, due to the increased pressure, while the gas hydrate formation temperature also increases. As the water depth becomes deeper and the pressure increases, the thickness of the methane hydrate stability layer also increases. BSR strong reflected signal means that there is gas hydrate. BSR is the maximum depth of gas hydrate formation. Above BSR, there lies the solid gas hydrate stability zone, while below it is the free methane gas.

The drilling results of U.S. Ocean Drilling Program 164 voyages (ODP leg 164) at Blake Ridge have confirmed the following: in the case of the absence of bottom-simulating reflection, sediments may still have gas hydrate occurrences. Therefore, if only depending on the survey of Parody seabed reflection distribution, it is likely to misjudge the actual distribution area of methane hydrate occurrence.

## 4. Gas hydrate investigation in southwest Taiwan seas and South China sea

Since 2001, Central Geological Survey (MOEA, Taiwan) has implemented a series of gas hydrate research and investigations in southwest Taiwan seas. Through the collection of geophysical, geochemical, and geological data, the total estimated methane reserve was found to be about 500–2700 billion cubic meters [35,36].

### 4.1. Central Geological Survey (MOEA)

Refer to Table 3 and Fig. 5. From 2001 to 2015, Central Geological Survey (MOEA, Taiwan) conducts a series of research projects to investigate and assess the marine gas hydrate in southwest Taiwan seas, which is mainly executed by Institute of Oceanography, National Taiwan University. In the preliminary stage of research and evaluation (2001–2003), the focus was on the establishment of database and web pages. In the first phase (2004–2007), three major areas of surveys and exploration were emphasized, namely, geophysics, marine geology, and geochemistry. Based on the survey methodology and the results of the first phase, the project of the second phase (2008–2011) estimated the

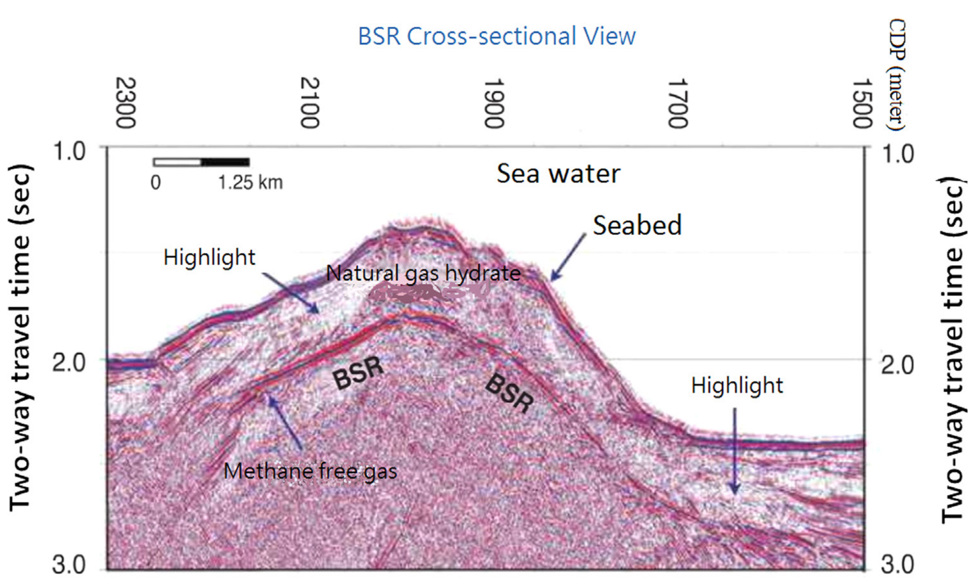


**Fig. 4.** Undersea simulating reflector on seismic section, if seismic reflection profiles are subject to strong undersea parody reflected signal, then there is gas hydrate. The solid gas hydrate stability zone is above BSR (Bottom Simulation Reflector), below is free methane gas. Gas hydrates are homogeneous solid, no reflective layers, so there will highlight the phenomenon. The larger are the extent and scope of highlight, the greater are the saturation and distribution range of gas hydrate [34].

**Table 3**
Gas hydrates survey and assessment projects by Central Geological Survey, MOEA [36].

| Year | Project | | Master plan | Execution unit |
|---|---|---|---|---|
| 2001 | Advance research and evaluation | Gas hydrate preliminary investigation research project on waters surrounding Taiwan | | Industrial Technology Research Institute |
| 2002 | | Taiwan southwestern seabed parody reflector (BSR) database and methane (natural gas) hydrate Web build projects | | National Taiwan University |
| 2003 | | Gas hydrates Earth Sciences advance survey in Taiwan southwestern waters | | National Taiwan University |
| | | Southwestern Taiwan gas hydrate database – submarine sonar echo-cum-sectional database and website build project. | | |
| 2004–2007 | First phase | Taiwan southwest marine area gas hydrate occurrence geological survey | Marine geological surveys and geochemical exploration | National Taiwan University |
| | | | Geophysical Investigations | National Taiwan University |
| 2008–2011 | Second phase | Southwestern Taiwan emerging energy – gas hydrates resources investigation and assessment | Seismic and geothermal surveys | National Taiwan University |
| | | | Geochemical survey | National Taiwan University |
| | | | Thermodynamic study | National Taiwan University |
| | | | Multi-tone water depth and bottom beam sonar survey | National Central University |
| 2012–2015 | Third phase | Gas hydrates resource potential investigation | Seismic, geothermal and geochemical research | National Taiwan University |
| | | | High-resolution sonar survey | National Central University |
| | | | Studies on thermodynamics and kinetics | National Taiwan University |

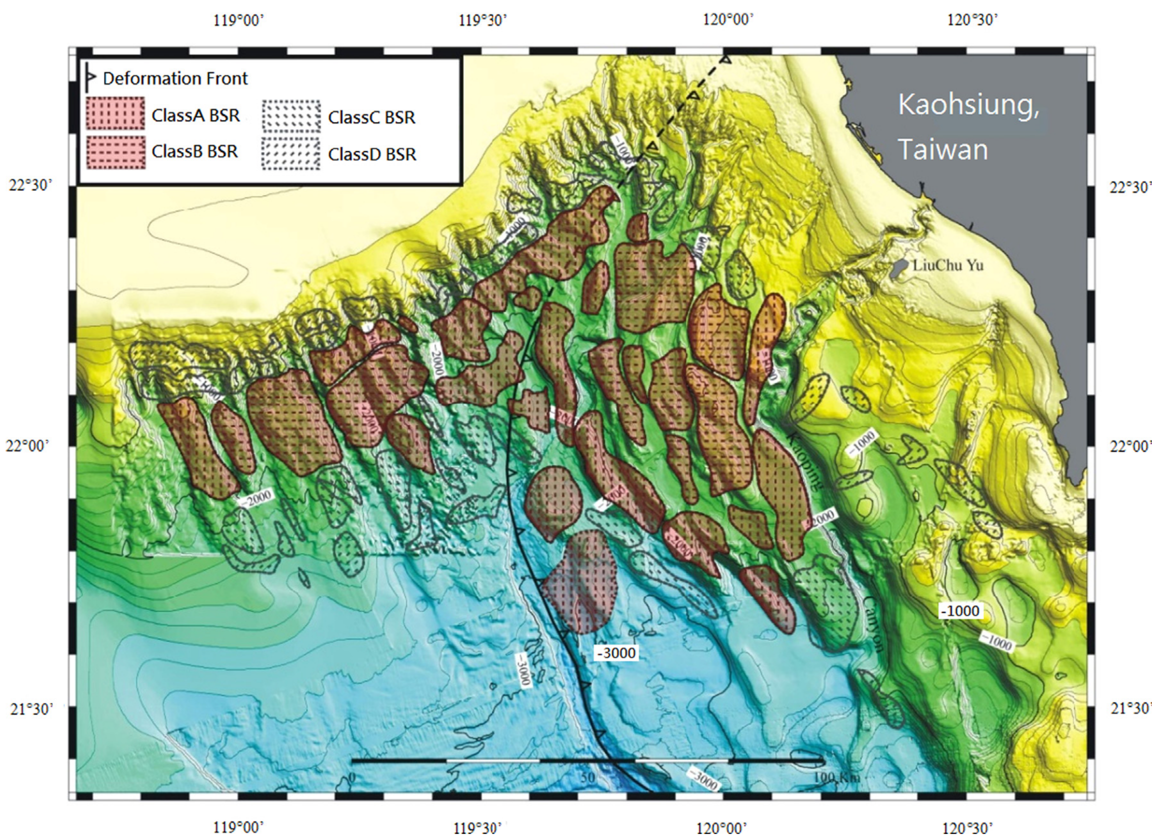


**Fig. 5.** Parody reflection map for Taiwan southwestern coast seafloor (Class A: high credibility BSR distribution; Class B: possible BSR distribution; mbsf: the meter below seafloor [37]). Gas hydrate distribution area covers 5000 square kilometers; the amount of natural gas resources are roughly 500–2300 billion $m^3$, equivalent to natural gas available supply about 50–230 years for domestic use (National Science and Technology Program-Energy Phase II Planning Report, Gas Hydrate Spindles Project).

natural gas hydrates reserves in the exploited area with new investigative techniques and equipment. The survey areas of the first and second phases are located in Kaohsiung–Hengchun deep seas. By means of the latest exploitation technology acquired from international cooperation, Phase 3 (2012–2015) project expands the exploration ranges to the entire South China Sea, in terms of gas hydrate distribution and reserves.

According to the assessment reports made by Central Geological Survey in 2011, the gas hydrates reserve off Taiwanese Pingtung coast is about 500–2700 billion cubic meters. Moreover, in the recent five years, the annual consumption of natural gas in Taiwan is about 10 billion cubic meters. If the gas hydrates reserved in southwestern Taiwan seas were fully developed, the natural gas supply of Taiwan would sustain for 50–270 years [36].

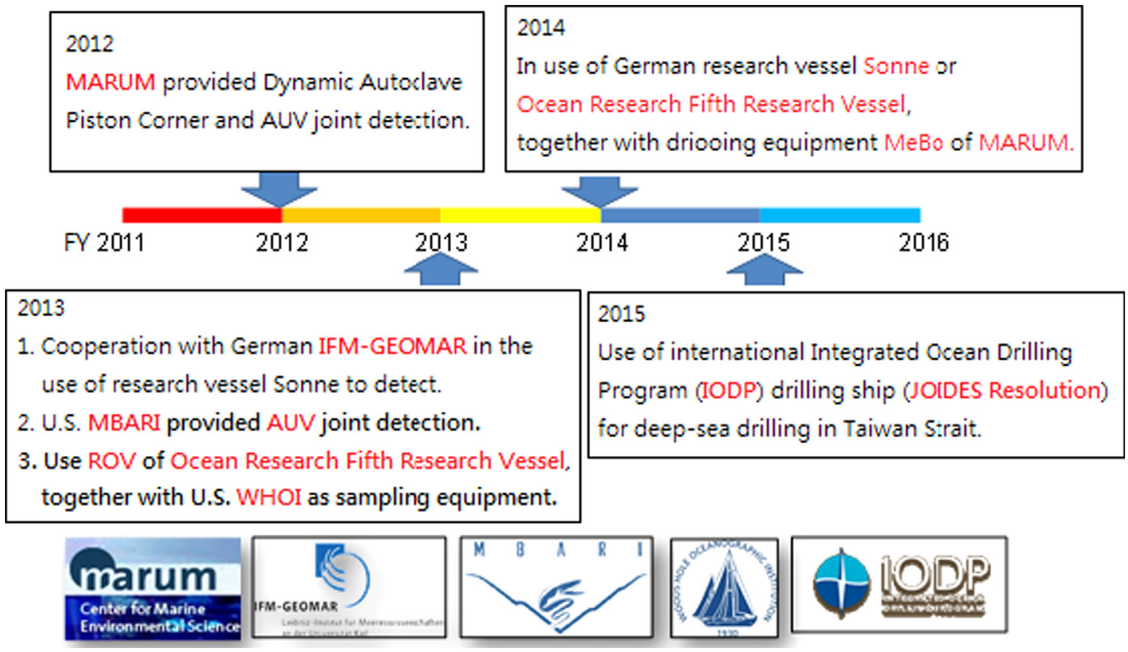


**Fig. 6.** Planning timetable of international cooperation projects (Gas Hydrates Spindle Project, NSTPE, Phase II Planning Report).

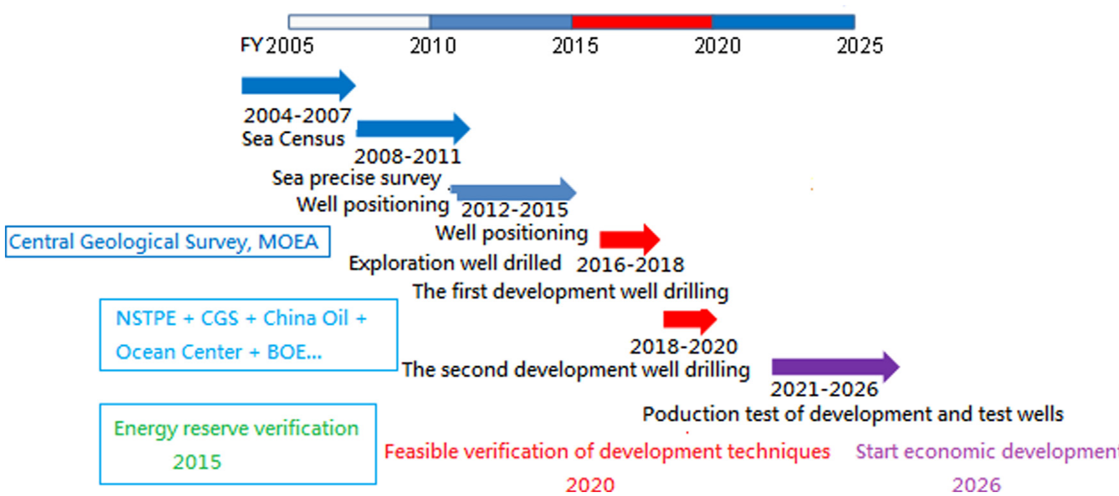


**Fig. 7.** Taiwan gas hydrate development and promotion processes (Gas Hydrates Spindle Project, NSTPE, Phase II Planning Report).

Also in 2011, the gas hydrates evaluation plan conducted by Central Geological Survey for off southwestern Taiwan seas used the Monte Carlo statistical simulation method. Along with the volume method applied in estimating the amount of hydrate resources in Japan Nankai Trough by Fujii et al. [38], one of the important parameters—the BSR distribution area—was applied. However, the geophysical properties of southwestern Taiwan seabed are different from those of Japan, such as porosity. In general, southwestern Taiwan seabed can be divided into continental slope zone and accretionary zone, in which the total amount of gas hydrate resources is up to 2.7 trillion cubic meters [35].

### 4.2. National Science and Technology Program-Energy

Basically, "National Science and Technology Program-Energy (NSTPE)" is the tenth National Science and Technology Program conducted by Ministry of Science and Technology, aiming to integrate all the domestic energy R&D resources in Taiwan. In 2008, NSTPE included the gas hydrate research and survey project executed by Central Geological Survey for southwestern Taiwan seas. In terms of pilot planning and design, the white paper was issued in 2011 and approved by Ministry of Science and Technology in 2013. "Gas Hydrates Spindle Project" was finally officially launched in 2014. Refer to Figs. 6 and 7. There are four main missions for "Gas Hydrate Spindle Project" under the supervision by NSTPE.

(1) Assessment of the gas hydrates resource characteristics in Taiwanese exclusive economic seas.
(2) Development of the R&D key technologies related to the production of gas hydrates.
(3) Study of the gas hydrates' impacts on the seabed slope stability and on the global environmental system; meanwhile, the evaluation models and countermeasures will be proposed as well.
(4) Research and development of the new gas hydrate technologies applied to the energy saving and carbon reduction, as well as the natural gas transport and storage, thereby promoting the related industries to improve the energy efficiency by reducing the proportion of carbon emissions.

**Table 4**
Architecture and major projects of "Gas Hydrate Spindle Project (NSTPE)".

| Category | Project | Execution unit |
|---|---|---|
| Resource characterization | Offshore drilling investigation and resource reserves assessment for natural gas hydrate | National Taiwan University |
| Production and development | Sea area detection and sampling technology of methane hydrate research and development | National Sun Yat-Sen University |
| Global carbon cycle | Potential impact assessments of high hydrocarbon emissions on environment stability | National Taiwan University |
| Exploration safety and seabed stability | Basic research of seabed geology and stability of Taiwan southwestern marine gas hydrate | National Central University |
| Energy transmission, energy storage and industrial applications | Studies of gas hydrate development, carbon dioxide sequestration theory, and practical reservoir engineering | National Taiwan University |
| Deep-sea biodiversity | Biodiversity and ecosystem study of deep-water natural gas hydrate occurrence area | National Taiwan University |

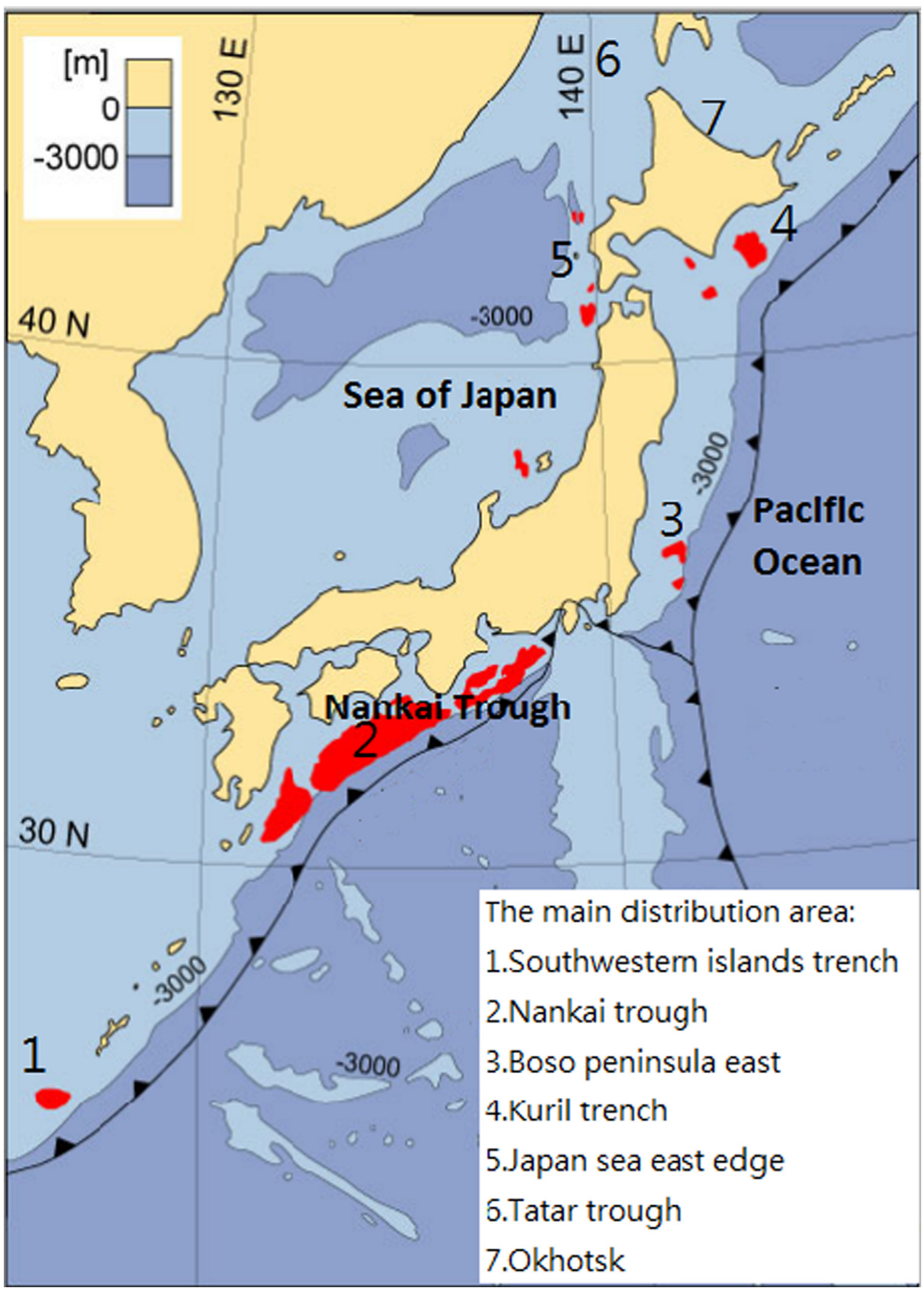


**Fig. 8.** Illustration of gas hydrates' main occurrence areas in Japanese surrounding waters (*Data source*: https://www.gsj.jp/Muse/eng/tour/two/meth.html).

The preliminary planning timetable for “Gas Hydrates Spindle Project (NSTPE)” has been divided into the following three terms:

(1) Near term: 1st–4th year.
(2) Intermediate term: 5th–9th year.
(3) Long term: 10th–15th year.

As shown in Table 4, the main R&D structure of “Gas Hydrates Spindle Project” is based upon six major items: (1) resource characterization; (2) production and development; (3) global carbon cycle; (4) exploration safety and seabed stability; (5) energy transmission, energy storage and industrial applications; and (6) deep-sea biodiversity. The Project has subsequently accepted research programs/projects from various parties including academia and institutes since 2013 and has begun to execute already since 2014.

## 5. Japanese methane hydrate development program

This section aims to explore the planning contents, current progress, and future prospects of the methane hydrate research and development program in Japan, which might benefit other countries.

With oil consumption ranked second in the world, Japan may be regarded as an economic power in the world, but its energy structure is very fragile, mainly because 98% of the energy demand is imported from foreign countries. The indigenous energy sources, like coal, oil, natural gas, etc., are very scarce in Japan, accounting for only 1–2% of the total national energy demand [39]. According to statistical analysis by EIA [40], Japan is the largest importer of liquefied natural gas, the second largest importer of coal, and the third largest importer of oil. Therefore, in order to maintain continuous economic growth and a stable supply of energy, Japan has been actively seeking and exploiting its own new energy resources, like solar energy, wind power, and gas hydrates.

According to the characteristics displayed by Bottom Simulating Reflector (BSR), the seas around Japan have abundant methane hydrates reserves, which are mainly distributed in the undersea troughs and basins of arc islands, including the southwestern islands trench, Nankai Trough, Boso Peninsula East, the Kuril Trench, Japan sea east edge, Tatar Trough and Okhotsk region, of which the total distribution area is about 44,000 $km^2$, as shown in Fig. 8. It is estimated that the methane hydrate reserves in Japanese seas (i.e., the total contained methane gas volume under the seabed) are about 4.7–7.4 trillion cubic meters referred at standard temperature and pressure [41–43]. In other words, the total gas hydrates reserve is equivalent to 40–63 times the national natural gas consumption in 2012 (116.7 billion $m^3$) [44].

In Japan, for all the methane hydrate plays, the development of Nankai Trough is the most frequent, and its average estimated reserve is also the highest. Only in Nankai Trough of eastern seas, there is about 1.14 trillion cubic meters reserve of methane [38,45]. Refer to Fig. 8. The Japanese Nankai Trough is located on the margins of Philippine Sea Plate and Eurasian Plate, where inter-collisions occur actively. The water depth of Nankai Trough is about 4800 m. Owing to the effect of plate subduction, a series of accretionary prisms were formed at one side of the arc islands facing the trough; thus Nankai Trough margin strata are mainly composed of the sediments accumulated on these accretionary prisms and forearc basins [20].

Japan is the first country to have invested a large number of funds to promote the methane hydrate resources survey and research. Since regarding methane hydrate as a new energy source in the 21st century, Japan has been actively carrying out a variety of related research and development programs. Especially, “Research Consortium for Methane Hydrate Resources in Japan (MH21)” is a cooperative research group founded by industry, government and academia in 2001. In July of the same year, MH 21 announced “Japanese Methane Hydrate R&D Program,” which is further divided into three implement phases. Phase 1 was completed in 2008, and Phase 2 began in 2009 and expected to be ended by 2015, while the planning term of Phase 3 is during 2016–2018.

Refer to Fig. 9 [45]. The goal of “Japanese Methane Hydrate R&D Program” is mainly to facilitate the successful development of commercial production technology for the methane hydrates distributed in Japanese offshore seabed. In order to actually present the program, international cooperation with innovative concepts is combined therein to develop the high-performance technologies. The related outcomes of the program will be reflected in the governmental energy policy as well. There are six sub-targets listed as follows:

(1) Clarification of the occurrences and characteristics of methane hydrate in Japanese offshore.
(2) Assessment of the methane gas amounts trapped in the promising methane hydrate-bearing offshore areas.
(3) Selection of methane hydrate resource fields from promising methane hydrate-bearing offshore areas and deliberation of economic potential.
(4) Implementation of the production test in the selected methane hydrate resource fields (until FY 2011).
(5) Improvement of technologies for the commercial production (until FY 2016).
(6) Establishment of a development system complying with the environment.

Refer to Fig. 9 [45]. There are totally three phases of 18 years in “Japanese Methane Hydrate R&D Program.” The mission contents can be abstracted separately as follows: (1) In the first term of total eight years from 2001 to 2008, Japan and Canada had cooperatively completed the Canadian terrestrial methane hydrate production tests; meanwhile the methane hydrates offshore seismic experiment and detection wells in Nankai Trough under Japanese eastern seas had been established as well. (2) In the second term of total seven years from 2009 to 2015, the methane hydrate production test in land has been already completed successfully; the next step will be the production and testing processes for offshore methane hydrates, aiming to extract the related techniques, define the related issues, and recommend the economical and efficient extraction methods. On the other hand, the overall Japanese offshore reserves of methane hydrate distribution will be assessed as well. (3) In the last three years of the third phase (2016–2018), the main goal will be the complete readiness for the commercial production. Meanwhile, the economic potentials and environmental impacts will be comprehensively evaluated.

## 6. U.S. methane hydrate development status

Refer to Fig. 10 and Table 5. According to the study completed in 1995 for the survey of the seas around the United States and the terrestrial permafrost in North America, the natural gas reserve of methane hydrate plays in the U.S. is about 9060 trillion cubic meters. The shares of the five main areas are as follows: Alaska seas (52.8%), West Pacific Ocean (19.1%), Gulf of Mexico (11.9%), Atlantic (16.2%), and Alaska land (0.2%).

Based on the above data, the methane resources contained in the gas hydrate plays under the U.S. jurisdiction are about 9060 trillion cubic meters. If 10% of the resources were recoverable, then there would be sufficient natural gas provided for the use of the

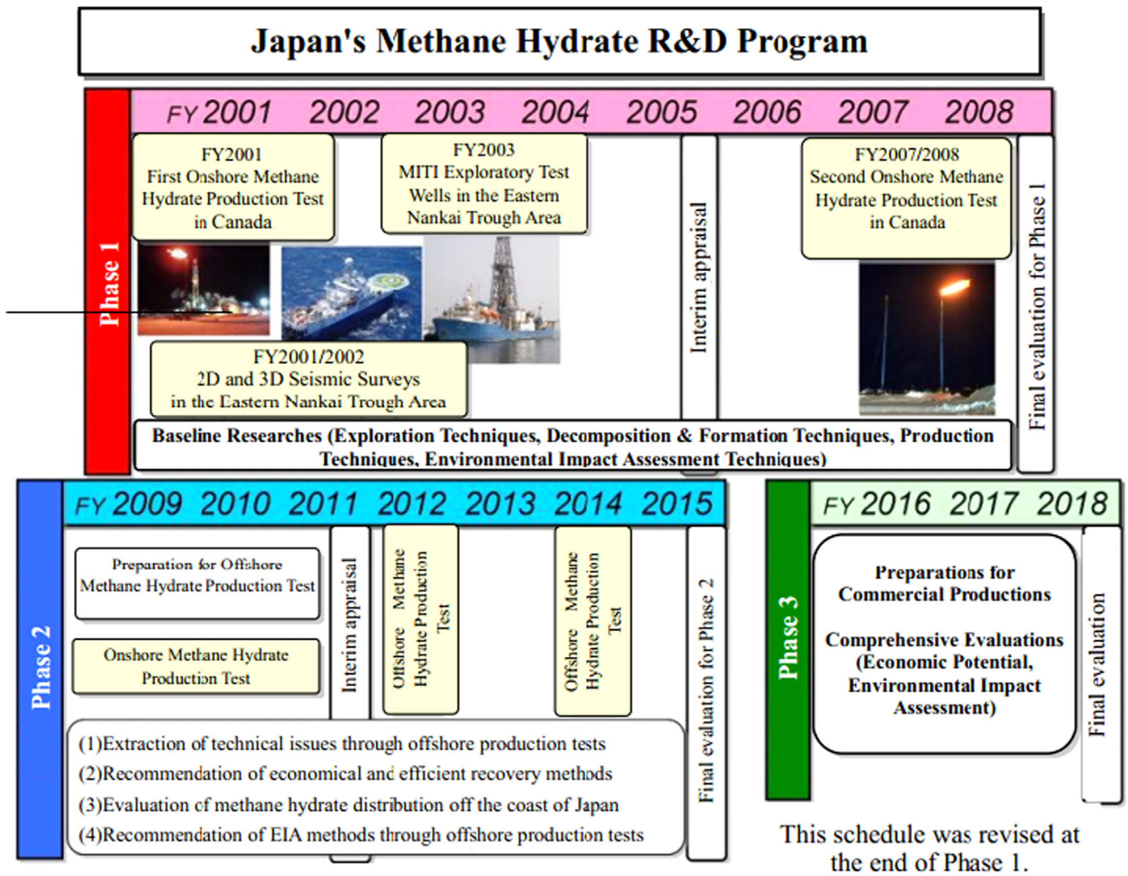


**Fig. 9.** Japanese three-phase methane hydrate research and development program with a total planning period of 18 years [45].

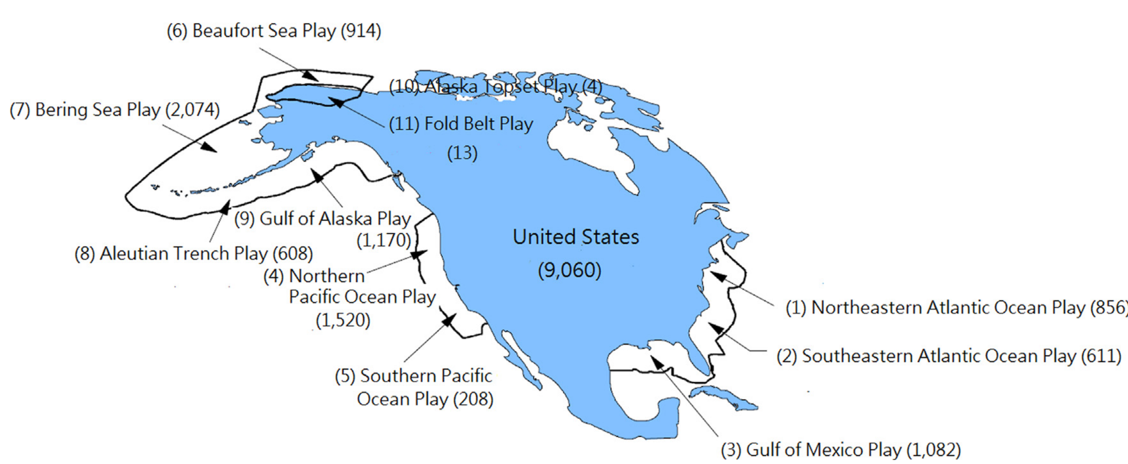


**Fig. 10.** Illustration of the U.S. methane hydrate plays distribution [46]. Figures in brackets denote the average methane hydrate resources estimated in each play (unit: trillion cubic meters ($10^{12}$ $m^3$)).

U.S. about 1255 years, based on the domestic annual natural gas consumption in 2012 (722.1 billion cubic meters) [44].

In terms of large gas hydrate field exploration, the United States currently has three main projects under way: the first one is the exploration of offshore marine hydrate in the Gulf of Mexico; the other two are the explorations of methane hydrates under the permafrost of northern Alaska land.

First of all, “Mexico Joint Industry Project (JIP Gulf)” is a joint research program, of which the key members are DOE and Industry Cooperation Alliance led by Chevron. The overall objective of “JIP Gulf” is to develop technology and obtain data to understand the characteristics of methane hydrates gathered under the deep water of the Gulf of Mexico. During 2009, the team successfully completed the drilling and logging project (JIP Leg II) in three different areas of the Gulf region by drilling a total of seven wells, which include the deepest gas hydrate research well in the world. Drilling and logging results show that there are indeed highly saturated sandy reservoirs of gas hydrates, thus confirming the validity of methane hydrate exploration methods. The names of these three exploration areas are Walk Ridge 313, Green Canyon 955, and Alaminos Canyon 21.

The drilling and logging results in 2009 are in line with the original scientific objectives and expectations. “JIP Gulf” found that the Gulf of Mexico has abundant natural gas hydrate sediments, while many high-quality geological data were produced as well. This drilling program improves the related techniques of

**Table 5**
U.S. methane hydrate plays and contained methane resource estimate averages [46,47].

| Area | Play | Methane resource and share | | |
|---|---|---|---|---|
| | | ($10^{12}$ $m^3$) | ($10^{12}$ $m^3$) | (%) |
| Atlantic waters | (1) Northeastern Atlantic Ocean | 856 | 1467 | 16.2% |
| | (2) Southeastern Atlantic Ocean | 611 | | |
| Gulf of Mexico | (3) Gulf of Mexico | 1082 | 1082 | 11.9% |
| Pacific Ocean | (4) Northern Pacific Ocean | 1520 | 1728 | 19.1% |
| | (5) Southern Pacific Ocean | 208 | | |
| Alaska waters | (6) Beaufort Sea | 914 | 4766 | 52.6% |
| | (7) Bering Sea | 2074 | | |
| | (8) Aleutian Trench | 608 | | |
| | (9) Gulf of Alaska | 1170 | | |
| Alaska Land | (10) Topset | 4 | 17 | 0.2% |
| | (11) Fold Belt | 13 | | |
| Total | | 9060 | 9060 | 100% |

detection, identification, and sampling of the hydrate in marine environment. The test wells confirmed the presence of methane hydrate resource indeed with good quality in selected locations. JIP is currently analyzing the collected data, and planning other appropriate drilling locations in order to make another expedition to further define the hydrate resource reserve area and amount.

In addition, DOE is also in cooperation with Geological Survey, BP, and other teams from the industry, government, and academia to conduct the assessments and tests for the hydrates' manufacturability in Arctic Alaska, where Geological Survey estimates that the natural gas hydrate accumulation is about 85 trillion cubic feet. The ultimate goal of this project is to assess the naturally occurring gas hydrate reaction when there is a reduction in control pressure. In 2007, the test wells drilled in Mount Elbert confirmed the existence of hydrate with a saturation of 60–75%. The short-term well tests also confirmed that the underground formation has the ability to release gases under controlled pressure reduction. This is the first relative test completed in Alaska North Slope.

Another Arctic Alaska project, led by ConocoPhilips, is planning to undertake a field experiment in Prudhoe Bay area, which is ready to test a method that produces methane via the exchange between $CO_2$ and $CH_4$. In this method, the carbon dioxide will be injected into the methane hydrate reserve area, where $CO_2$ molecules will be exchanged with methane molecules in situ, and then the methane is released to complete the production. If successful, this will probably be a realization of "Synergistic Approach" for both the carbon dioxide sequestration and the methane hydrates' mass production.

Overall, there are abundant methane hydrates reserved in the United States jurisdiction, no matter in land or sea. Currently, the three major plays in the U.S. are the sandy layers in the southern Gulf of Mexico, the Alaska Arctic permafrost and the seas. For a complete understanding of the methane hydrate as a potential natural gas resource and the impacts on the environment, the United States has been actively promoting a variety of methane hydrate research programs since 2000. The research items include: the resource characteristics, production, global carbon cycle, security and stability of the seabed. The urgent methane hydrate R&D goal of the United States is to complete the commercial development and potential assessment for the methane hydrate resources in Alaska North Slope Permafrost by 2015. The second goal is the proof of technical feasibility of the further production of methane hydrate resources in the seas by 2025. Meanwhile, the economic feasibility for mining the methane hydrate resources contained in the sandy layers in the seas should be assessed as well. In other words, preparation for the commercial development for the methane hydrate resources in the Gulf of Mexico would be completed in the next decade [48].

## 7. Chinese gas hydrates investigation program

Currently, China has been focusing its gas hydrate research activities on the Tibetan Plateau and South China Sea [49,50]. It is estimated that Chinese land gas hydrate reserve in the long term is at least 35 billion tons of oil equivalent, and the marine methane reserve in the South China Sea is about 64 billion tons of oil equivalent.

Since 1999, China has begun its gas hydrate resources survey in the northern South China Sea. In the use of multi-channel seismic reflection technique with high resolution, the BSR characteristics were found. Meanwhile, in 2002, China launched "Chinese Marine Gas Hydrate Resources Survey and Evaluation Program", which had carried out a series of investigation activities, in terms of geophysics, geochemistry, and water depth in the northern South China Sea. As a result, the program preliminarily mastered the information related to the distribution and thickness of gas hydrate. Subsequently, in 2004, in cooperation with German Kiel Leibniz Institute of Marine Sciences, Guangzhou Marine Geological Survey discovered the largest seep carbonates in the world – the Kowloon beach methane reef in the southern marine slope of mainland China (Fig. 11). Kowloon methane reef carbonates are white coarse seepage carbonates formed by the action of microorganisms, which can be caused by the decomposition of gas hydrate deposition. This means a significant possibility of a very large gas hydrate reserve present in this marine area.

In addition, in 2007, it took 52 days (04/21–06/12) for the Guangzhou Marine Geological Survey to implement the gas hydrate drilling surveys in southwestern Dongsha Islands of the northern South China Sea. The survey mission included the drilling of eight guide wells and the extraction of five cores, in which three cores indeed contain gas hydrate samples. As shown in Fig. 12 and Table 6, the gas hydrate resources are located in the formation below the seabed about between 150 and 200 m. The thickness is about 10 or 25 m, while the saturation is less than 50%, and the methane gas dissociation content is over 99%. The survey results show that 11 combustible ice ores were designated, respectively, in the targeted seas within the area of 140 $km^2$. Under estimation, the total minable area is about 220,000 square kilometers, while the average ore bed thickness is about 20 m, and the methane reserve is about 19.4 billion cubic meters.

Guangzhou Marine Geological Survey currently has delineated the South China Sea into 25 mines, which means that the resources' availability has reached 4.1 billion tons of oil equivalent. In the northern South China Sea, seven potential mines and 19 metallogenic belts have been delineated. Only in Shenhu seas, 11 sites for drilling and exploring marine gas hydrate have covered a wide area of 23 square kilometers [36].

Starting from 2011, China officially launched a new national hydrate program, which will last for 20 years from 2011 to 2030, and will be implemented in two phases. The first phase (from 2011 to 2020) aims to further explore and evaluate the gas hydrate-rich regions, for setting up the foundations of trial mining, exploitation, and industrial realization for the gas hydrates in South China Sea. According to the program, China will implement both the marine research results and the supportive techniques for further hydrate trial production, on the basis of the exploration and evaluation of data acquired before.

In June 2009, China successfully drilled out the physical samples of combustible ice from the southern edge of permafrost in Qilian Mountains, Qinghai Province, becoming the first country

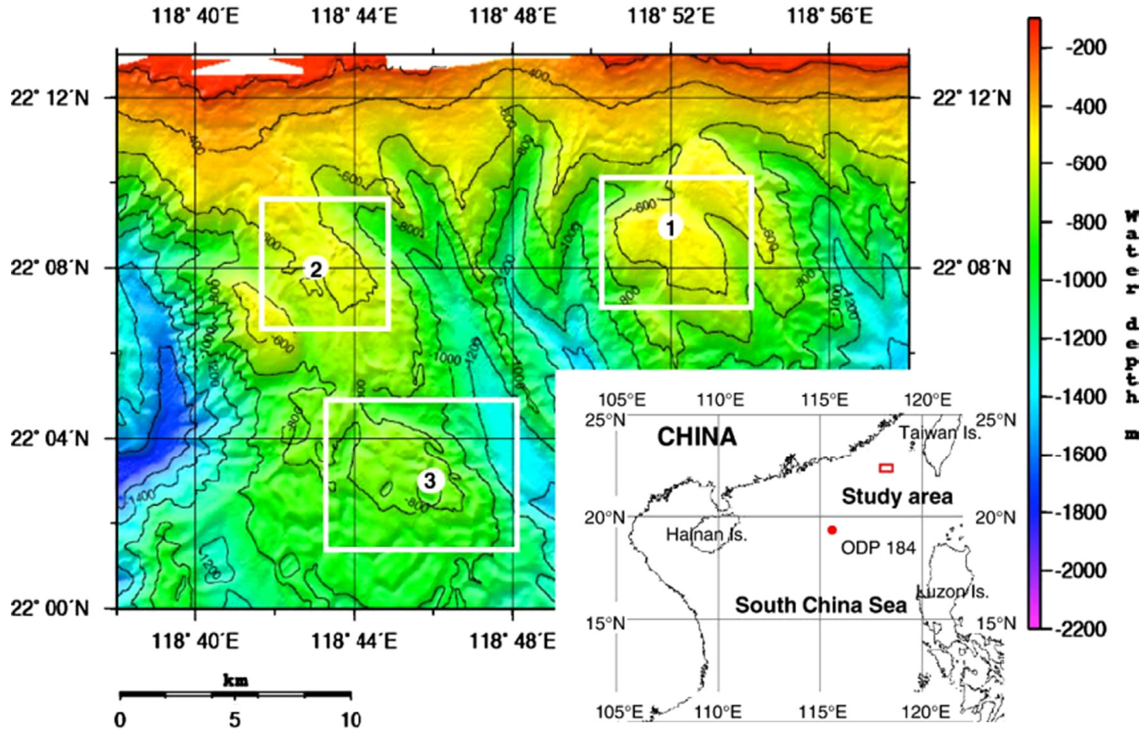


**Fig. 11.** Kowloon methane reef range chart [51].

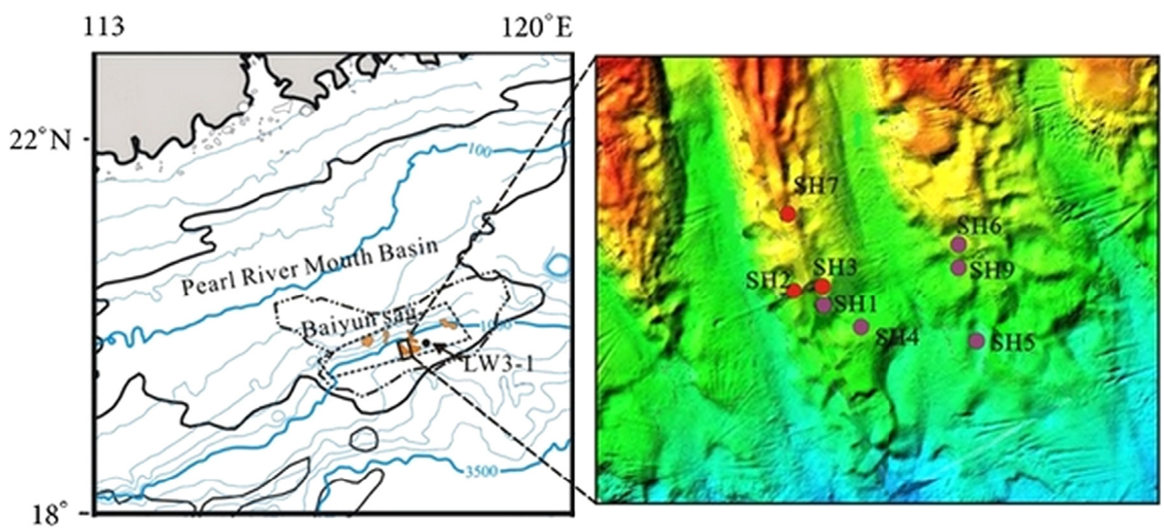


**Fig. 12.** Areas of gas hydrate exploration and drilling area with drilling sites in the northern part of the South China Sea [52]. (Red dots: gas hydrate samples obtained; dark purple dots: no gas hydrate samples obtained). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 6**
Shenhu marine natural gas hydrates drilling basic data [52].

| Natural gas hydrate samples | SH2 | SH3 | SH7 |
|---|---|---|---|
| Sea bed depth (meter) | 195–220 | 196–206 | 152–177 |
| Thickness (meter) | 25 | 10 | 25 |
| Saturation (%) | 25–47 | ≤ 25 | ≤ 43 |

in the world to discover combustible ice in low-latitude permafrost zone. According to the estimates by experts, the prospective reserve of combustible ice in the Qinghai-Tibet Plateau is about 35 billion tons of oil equivalent, accounting for 1/4 of the entire China land, which can sustain the domestic natural gas use for about 90 years [32].

## 8. Other countries

### *8.1. Canadian gas hydrate exploration program*

Gas hydrate, a solid form of natural gas and water, is inferred to occur widely in Canadian polar and continental shelf regions and in the sediment of outer continental margins. Although direct indications of hydrate are few and widely separated, conditions are potentially favorable for gas hydrate formation and stability, especially in low to moderate temperatures under permafrost or the deep sea, combined with favorable geological conditions for gas generation and storage, covering vast areas and indicating an immense potential, natural hydrocarbon gas was substantially found in the upper 2 km of many Canadian sedimentary basins. By analyzing the potential of gas hydrates for the vast continental

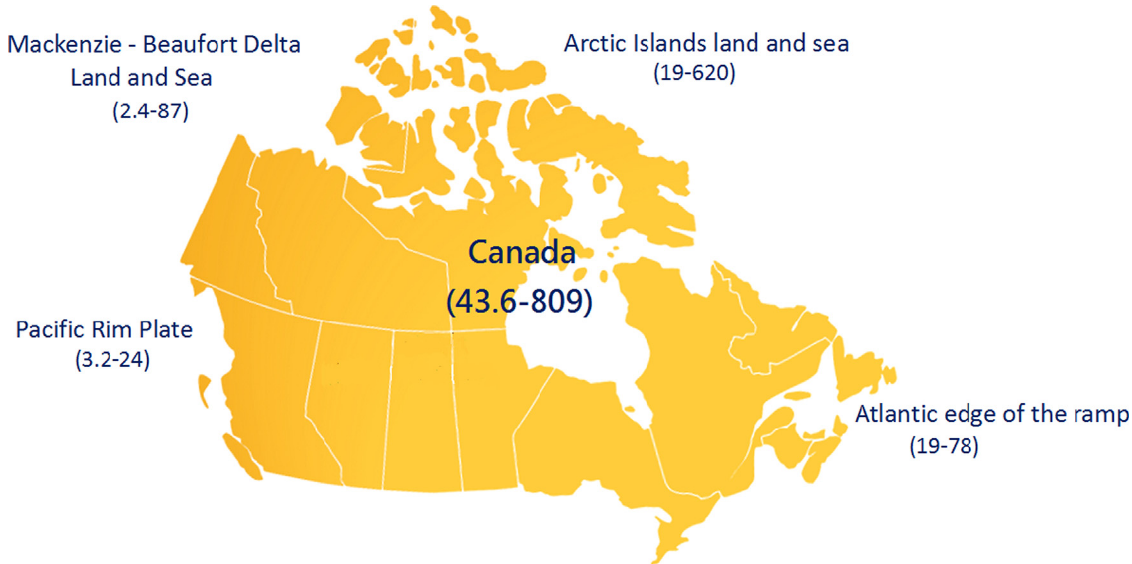


**Fig. 13.** Illustration of Canadian methane hydrate plays distribution [53]. Figures in brackets denote the average methane resources estimated in every major region (unit: trillion cubic meters ($10^{12}$ m$^3$)).

**Table 7**
Indian methane hydrate reserves (trillion cubic meters) [54].

| Play | Reserves (TCM) | | |
|---|---|---|---|
| | 95% probability | 50% probability | 5% probability |
| Bombay offshore | 135 | 454 | 852 |
| Kerala-Konkan offshore | 62 | 1137 | 2299 |
| North Arabian sea | 226 | 595 | 1092 |
| South Arabian sea | – | 312 | 1094 |
| Eastern offshore | 1038 | 2168 | 4525 |
| Bay of Bengal | 245 | 468 | 937 |
| S Bay of Bengal | 188 | 1022 | 3773 |
| TOTAL | 1894 | 6156 | 14,572 |

shelves and Arctic permafrost regions of Canada (Mackenzie delta-Beaufort Sea and Arctic Archipelago in the north and Davis Strait, the Labrador Shelf, Scotian Shelf, and Grand Banks of Newfoundland along the Canadian Atlantic margin and Canadian Pacific margin), the conservative evaluation suggests $10^{10}$–$10^{12}$ m$^3$ of gas hydrates in these regions has an associated methane gas potential estimated to be in the range of $10^{12}$–$10^{14}$ m$^3$. As shown in Fig. 13, the volumes of methane in hydrates in Canada are geographically distributed in the following regions: 0.24–8.7 $\times$ $10^{13}$ m$^3$ in the Mackenzie delta-Beaufort Sea, 0.19–6.2 $\times$ $10^{14}$ m$^3$ in the Arctic Archipelago, 1.9–7.8 $\times$ $10^{13}$ m$^3$ on the Atlantic margin, and 0.32–2.4 $\times$ $10^{13}$ m$^3$ on the Pacific margin. The total in-situ amount of methane in hydrates of Canada is estimated to be 0.44–8.1 $\times$ $10^{14}$ m$^3$, as compared to a conventional Canadian in-situ hydrocarbon gas potential of approximately 0.27 $\times$ $10^{14}$ m$^3$. This comparison suggests that gas hydrates represent a possible future assurance of North American energy supply, if the gas can be recovered and separated from the hydrate form [53].

### 8.2. Indian gas hydrate exploration and development program

Like Japan, India is a country that lacks traditional energy resources. However, as shown in Table 7 and Fig. 14, methane-rich ice has been found in the Indian Ocean, which is available for domestic use for hundreds of years if recovered into natural gas. Eager to exploit the methane ice within its own jurisdictions, Indian Scientific and Industrial Council initiated “National Gas Hydrate Research Program” in 1997. However, many European and American scientists are very worried about the move, because India is not as well-funded as Japan. So because of the shortage of funds, during the process of recovering methane ice, it might result in the loss of methane to the atmosphere, which is more serious than the greenhouse effect caused by carbon dioxide emitted from anthropogenic activities.

Anyway, the Indian government is still devoting a large program to the exploration of gas hydrate within its jurisdiction to meet its growing gas requirements. Seismic data have been acquired on the Indian continental margins, and current plans have also been called for drilling the dedicated wells for coring the gas hydrate. In addition, gas hydrates were recently discovered during the drilling of conventional oil and gas resources in the Krishna–Godavari Basin along the eastern coast of India.

## 9. The advent of natural gas era

The recent hottest energy topic is “Russia and China Gas Cooperation Treaty” signed by both the countries' representatives in Shanghai on 21 May 2014. The Treaty's outline is that Russia will gradually increase the natural gas supply to China from 2018, eventually reaching 38 billion cubic meters per year for 30 years. The total commercial worth is 400 billion USD. This Sino-Russian energy cooperation has a deep influence on economic and political stability in eastern Asia. In other words, the petroleum and gas conflicts in Diaoyu Island and South China Sea will be virtually mitigated.

### 9.1. The rise of natural gas

Through the energy cooperation between China and Russia, not only both the economic and energy security problems can be solved, more significantly the global rising trend of natural gas supply has been formed. Basically, in fossil-fueled power plants, the carbon dioxide emitted from natural gas combustion is about half that of coal, and about two-thirds of oil [55]. Therefore, natural gas has a pivotal position among the strategies to mitigate the global climate change caused by the greenhouse effect. Virtually, natural gas becomes an important bridge between the fossil fuels and the carbon-free energies (e.g., renewables and nuclear fusion.). Thus, the exploitation and application of natural

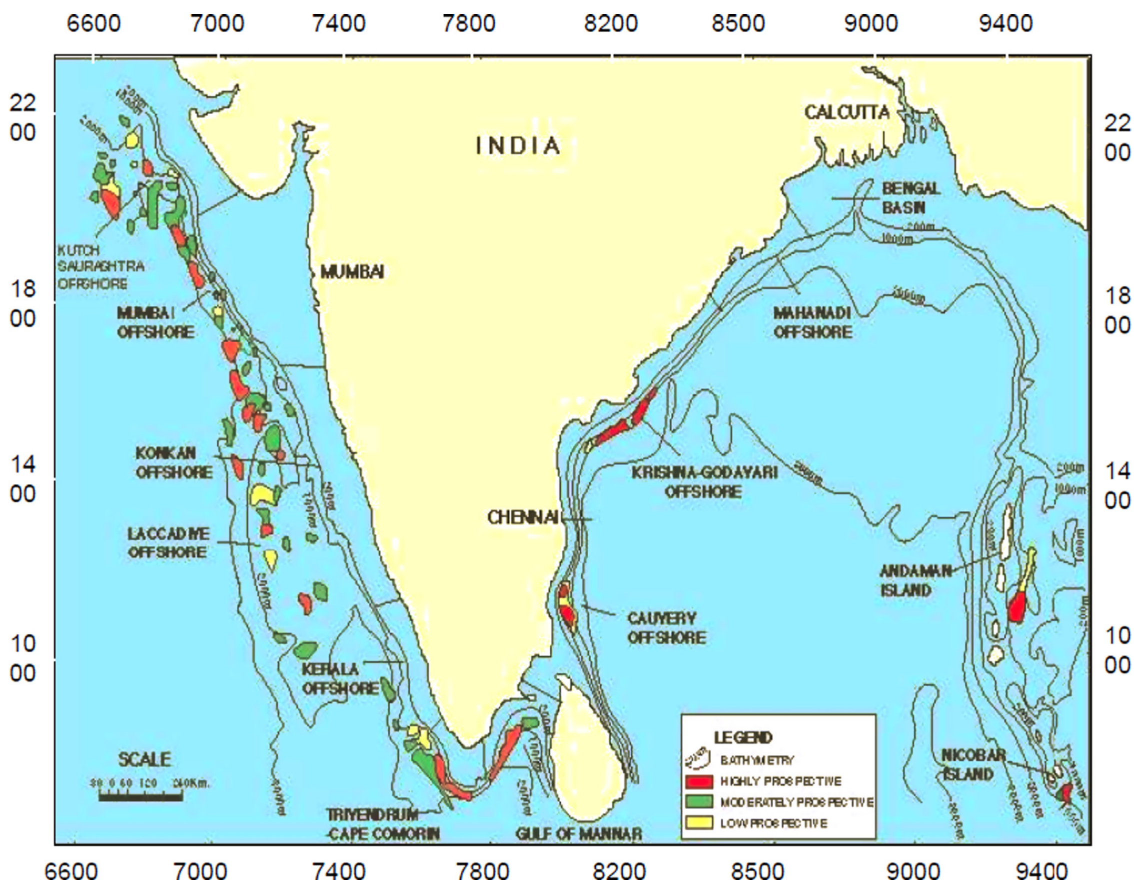


**Fig. 14.** Indian deep-water gas hydrate regions with forward-looking reserves [54].

gas have boomed recently. In addition to the exploitation of U.S. shale gas [56], Japan is ready for the gas hydrate commercial production in Nankai Trough after 20 years' efforts in exploring and drilling. The date for Japan to complete the related technology development is expected by 2018 [20]. Followed by the second phase of NSTPE conducted by Ministry of Science Technology, Taiwan will further promote the evaluation and assessment for gas hydrate reserve off Pingtung southwestern coast. The estimated methane is sufficient for Taiwan's natural gas use for at least 50 years [36].

### 9.2. Gas technology

In addition, natural gas is a versatile energy, which can be used in heating, cooking, and power generation. However, in the long term, natural gas just has not yet been used as a kind of fuel in the transportation sector, at least until now. Researchers in the United States have now found a new and more effective method to convert the main component of natural gas into liquid that is further refined to common bulk chemicals or fuels. This research opens the door for the energy sector to replace the rich gas with the depleting oil. This phenomenon results in the enhancement of the security of energy supply, the promotion of economic prosperity, the reduction of the reliance on oil throughout the world, the mitigation of the greenhouse effect caused by carbon emissions, and the prevention of the disasters brought about by global climate change; thus it can really be said that the rise of natural gas is indeed another energy revolution for the entire human society [57]. In short, this treaty signed by Russia and China is an excellent example to implement a successful energy policy. In general, the connotation of energy policy can be decomposed into the following six aspects: security, economy, science and technology, environment, cooperation, and regulation. Taiwan is in lack of indigenous energy resources, so 97% of the energy demand is imported from foreign countries [58]. It is not easy for both China and Russia to sign up this energy cooperation treaty that took at least ten years after all, and thus which is sufficient to be emulated by Taiwan in the formulation and implementation of its national energy policy.

### 9.3. Gas power generation

Based on the above-mentioned reasons, many domestic scholars have proposed the replacement of coal-fired power plants with gas-fired power plants. According to the energy statistics, the share of gas power generation in Taiwan had jumped from 13.2% in 2002 to 26.9% in 2012. Relatively, the power generation amount has also grown 1.56 times. With this increasing trend, gas power generation indeed has the chance to become the main power supply in Taiwan [58]. However, considering both the economic and energy security aspects, the price of gas used in domestic power generation is about twice the price of coal. Furthermore, the security reserve of gas is about one-half of the coal in Taiwan. The main cause of this disadvantage in terms of gas-fired power generation is that Taiwan is an isolated island in the Pacific. All the imported gas is Liquefied Natural Gas (LNG), which is different from the gas transported by the pipe system in Europe or North America. The additional procedures in LNG liquefaction, storage and transportation are the main reasons for the higher cost of gas power generation in Taiwan [7]. Japan, with a similar geographical environment to Taiwan, after the 311 nuclear disaster, has to increase the gas-fired power generation to make up for the shortage of power generation due to the stopping of running of nuclear power plants, whereby the price of LNG was surged up

**Table 8**
2010 all kinds of power generation costs (TWD/kWh)[a].

| | Construction cost (100 TWD/kW) [60] | | Usage year [61] | Capacity factor [61,62] | Maintenance cost (TWD/KWh) [60] | Fuel cost (TWD/kWh) [63] | Power generation cost (TWD/kWh) |
|---|---|---|---|---|---|---|---|
| | 2010 | 2020 cost down (%) | | | | | |
| Coal-fired | 400.3 | 1.57 | 35 | 0.85 | 0.23 | 1.04 | 1.42 |
| Coal-fired + CCS | 543.7 | 5.45 | 35 | 0.85 | 0.31 | 1.04 | 1.56 |
| Gas-fired | 179.7 | 2.75 | 35 | 0.87 | 0.1 | 3.94 | 4.11 |
| Gas-fired + CCS | 310 | 5.51 | 35 | 0.87 | 0.16 | 3.94 | 4.22 |
| Oil-fired | 224.7 | 0.00 | 30 | 0.41 | 0.1 | 5.47 | 5.78 |
| Nuclear | 1054.1 | 0.00 | 40 | 0.90 | 0.36 | 0.34 | 1.03 |
| Hydro | 505.5 | 0.00 | 40 | 0.53 | 0.18 | 0 | 0.45 |
| Wind (Land) | 389.6 | 7.15 | 25 | 0.33 | 0.2 | 0 | 0.74 |
| Wind (Marine) | 1028.1 | 17.53 | 25 | 0.33 | 0.4 | 0 | 1.82 |
| Solar (PV) | 1113.4 | 24.54 | 30 | 0.25 | 0.1 | 0 | 1.79 |
| Biomass | 853.3 | 0.00 | 20 | 0.83 | 0.5 | 0.1 | 1.19 |
| Waste | 499.2 | 0.00 | 30 | 0.52 | 0.5 | 0 | 0.87 |

[a] Currency rate: 1 USD = 30 TWD.

since then. According to specific energy calculation, the current price of LNG in Japan is about 16.76 USD/million BTU, which is approximately 3.60 times the natural gas price in the U.S. [59]. As shown in Table 8, other advantages for natural gas as fuel in power generation are as follows: according to the International Energy Agency data, the construction cost of gas-fired power plant is particularly cheap, less than one-half of the coal-fired power plants, and also about one-tenth of nuclear power plants.

Meanwhile, the gas power plant maintenance/operation cost is also the cheapest, and its construction time is much shorter than that of a nuclear power plant [60]. In addition, gas power plant can be started rapidly, therefore often as the major role in regulating the peak load in Taiwan. In short, with the surging rise of natural gas worldwide, the anti-nuclear wave, and the merits of a best energy policy, the development of natural gas into main energy supply is being looked forward to by the entire human society.

## 10. Conclusions and perspectives

Gas hydrate is one of the emerging clean energies of the 21st century. The prospective methane contained in global gas hydrate reserves is 21,000 trillion cubic meters [36], which are about 100 times the total natural gas reserves in the current world. Assuming 10% of the total reserves were exploited, it can be used for about 600 years, as shown in Tables 9 and 10 [44].

The current survey data show that along the southwestern Taiwan seas, the methane gas hydrate reserve in the deep waters off the coast of Tainan–Pingtung coast is approximately 2.7 trillion cubic meters [36]. If 10% of these resources were exploited, the estimated economic benefit is about 4 trillion NTD, based on the average natural gas price of 15.41 NTD/cubic meter announced by China Petroleum Company on 2 January 2010. Meanwhile, the estimated environmental benefit will be about 7.45 million tons of $CO_2$ emission reductions. In recent years, the average annual natural gas consumption in Taiwan is about 10 billion cubic meters. If methane gas hydrate resources in southwestern Taiwan seas can be fully developed, under conservative estimate, it can supply Taiwan with natural gas use for 270 years. Under the implementation of “Gas Hydrate Spindle Project” in NSTPE, Taiwan can grasp the opportunity to become an energy-independent country. As soon as the exploitation technology of gas hydrate becomes mature, the dependence on imported energy can be reduced significantly. Meanwhile, the impacts of international energy crisis on Taiwan can be mitigated to further ensure the security of national energy supply.

**Table 9**
Conventional gas consumption and reserves in the world in 2012 [44].

| Country | Conventional gas consumption (billion cubic meter) | Conventional gas reserve (trillion cubic meter) |
|---|---|---|
| US | 722.1 | 8.5 |
| Canada | 100.7 | 2.0 |
| Taiwan | 16.3 | – |
| Japan | 116.7 | – |
| India | 54.6 | 1.3 |
| China | 143.8 | 3.1 |
| World | 3,314.4 | 187.3 |

**Table 10**
Gas hydrate reserves and usage years in major countries.

| Country | Gas hydrate (trillion cubic meter) | Usage year |
|---|---|---|
| US | 9060 | 12,547 |
| Canada | 43.6–809 | 433–8034 |
| Taiwan | 50–230 | 50–230 |
| Japan | 4.7–7.4 | 40–63 |
| India | 1894–14,572 | 34,689–266,886 |
| China | 107.7 | 749 |
| World | 20,000 | 6034 |

Meanwhile, 1 $m^3$ of gas hydrate can store 150–180 $m^3$ of natural gas and 0.8 $m^3$ of water [64,65]. Furthermore, at atmospheric pressure and ambient temperature of $-20\,^{\circ}C$, the dissociation rate of the “combustible ice” is extremely slow, which is appropriate for long-term preservation. Therefore, gas hydrate essentially has a potential application as gas storage media. As the equipment demand for the supply chain of natural gas hydrate storage and transportation is relatively simple, with the advantages of mobility, safety, environment-friendliness, and economic benefit, gas hydrates may basically become the storage and transportation system needed by the commercial developers of small and medium gas fields, with the annual output of about 2 million tons and the transport distance of about 1000–6000 km, respectively. Japan, in addition to sparing no efforts to promote the research and development of gas hydrate storage and transportation technology, has been gradually constructing the supply chain infrastructure of gas hydrate storage and transportation. Japan has currently completed onshore natural gas hydrate storage and transportation supply chain demonstration projects, and has begun to build gas hydrate production factory with a daily output

of up to 100 t, which will become the transport chain infrastructure to promote offshore gas hydrate demonstration projects, expecting one to achieve the industrialization goals of gas hydrates storage and transportation supply chain business, the technical development of which deserves more international attention [66].

Based on the global consumption and proven reserves of fossil energy sources in 2012, conventional gas and oil can be used for about another 57 years [44]. However, with the rapid development of economies, the global energy demand has been increasing substantially. Every country in the world might have to face the early arrival dilemma of traditional energy deficiency. Therefore, apart from actively developing green energies, such as solar and wind power and other renewable energy sources, many countries also aggressively engage in the development of non-conventional fossil energies. The recent rise of U.S. shale gas is the best example. In contrast, the related technology research and development of methane hydrate resources is also highly expected by other countries.

Gas hydrate is likely to become a new type of natural gas resources. Although not belonging to a carbon-free energy, natural gas without doubt is the cleanest fossil fuel. For example, in fossil-fueled power plants, the carbon dioxide emitted by gas is only one-half of the coal and two-thirds of oil [67]. Also in considerations of seabed stability in addition to carbon reduction, the development of methane hydrate resources has gradually evolved into an innovative engineering concept/method by injecting the carbon dioxide into gas hydrate mine to replace methane, or with carbon sequestration technology, combining the injected carbon dioxide with gas hydrate decomposition byproduct – water – to interactively generate carbon dioxide hydrate, thereby storing the solidified carbon dioxide in the permafrost or in the seabed, thus achieving a win–win goal of methane production and carbon reduction. In short, the current trends of scientific and technological research for methane hydrate resources are towards the directions of developing and utilizing the carbon-neutral energies.

Taiwan lacks traditional energy sources; nearly 97% of the energy supply is imported from abroad. The above survey data confirms that Taiwan does have a huge methane hydrate resource. While the Ministry of Science and Technology has set up “Gas Hydrate Spindle Project” since 2014, the investment and scale are still far behind major countries in the world. The development of methane hydrate significantly relates to national security in terms of energy supply, and it is also a forward-looking project in the long term with high risk and high profit, which demands a substantial investment of manpower and funding from the governmental departments such as energy, economy, science and technology to develop the large-scale resource exploration and extraction technology. At the same time, considering the lack of manpower and funds in Taiwan, we suggest the international joint cooperation with neighboring countries, e.g., China, Japan, Korea, the Philippines, and Vietnam, in addition to the international cooperation already with the United States and Germany originally planned in the “Gas Hydrate Spindle Project.” After all, without the forward-looking technologies and sophisticated equipment from advanced countries, it is almost impossible to bear this major challenge—the explorations of energy source treasure stored in the seabed or under permafrost—gas hydrate.

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## Glossary

BP: British Petroleum;
BSR: Bottom Simulating Reflector;
CDP: Common Depth Point;
DOE: Department of Energy;
EIA: Energy Information Agency;
JIP: Joint Industry Project;
kWh: kilo Watt hour;
LNG: Liquefied Natural Gas;
mbsf: meter below seafloor;
MH21: Research Consortium for Methane Hydrate Resources in Japan;
MOEA: Ministry of Economic Affairs;
NTD: New Taiwan Dollar;
NSTPE: National Science and Technology Program-Energy;
ODP: Ocean Drilling Program;
SH: Shenhu;
TCM: Trillion Cubic Meters;
TWD: New Taiwan Dollar;
USD: US Dollar.